

## Designing for ESPA: The Challenges of Designing a Spacecraft for a Launch Accommodation Still in Development

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**Abstract:** The Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapter (ESPA) is a joint program developed by the DoD Space Test Program and the Space Vehicles Directorate of the Air Force Research Laboratory. It is designed to carry six small satellites as secondary payloads, weighing up to 400 pounds each, as well as a 15,000-pound primary payload into space on the next generation of expendable US launch vehicles.

The purpose of this paper is to present the small spacecraft user community with its first insight into the unique challenges of launching on the Delta-IV/ESPA configuration, based on experiences from the Space Test Program Mission 1 (STPSat-1) mission. Specifically, this paper addresses the issues associated with designing a spacecraft while the launch vehicle system is still under development, and the launch conditions and environments have not been completely characterized. It also explores the design approaches used to accommodate a cantilevered launch configuration. The paper also discusses how the STPSat-1 spacecraft design has been optimized for this launch vehicle, including specific design elements that minimize support requirements from the launch vehicle, both during the pre-launch integration phase and during launch itself. Lessons learned and recommendations for future payloads are also included.

### What is ESPA?

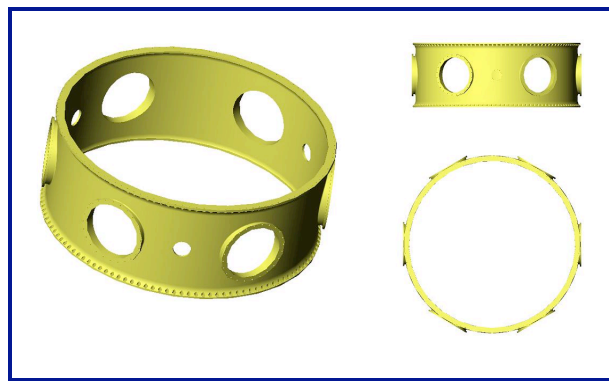
The ESPA (EELV Secondary Payload Adapter) ring is a system – developed by CSA Engineering under an Air

Force Research Laboratory (AFRL) Space Vehicles Directorate contract, in cooperation with the Department of Defense (DoD) Space Test Program (STP) – which provides secondary payload launch

capability aboard the new Evolved Expendable Launch Vehicles (EELVs). This new capability represents a significant growth in potential launch opportunities for small secondary payloads on US-based launch vehicles. The first flight of the ESPA ring is currently manifested aboard STP-1, a Boeing Delta-IV Medium launch vehicle, scheduled for launch in early 2006. At this writing, the ESPA is slated to carry four secondary payloads.

### How Does ESPA Work?

The ESPA ring (Figure 1) bolts onto the primary launch vehicle below the primary payload PAF (payload adapter fairing). After the secondary payloads are attached to the ESPA ring, the primary payload and the PAF are attached to the top of the ESPA ring and the entire assembly is encapsulated.



**Figure 1. ESPA Ring Structure.**

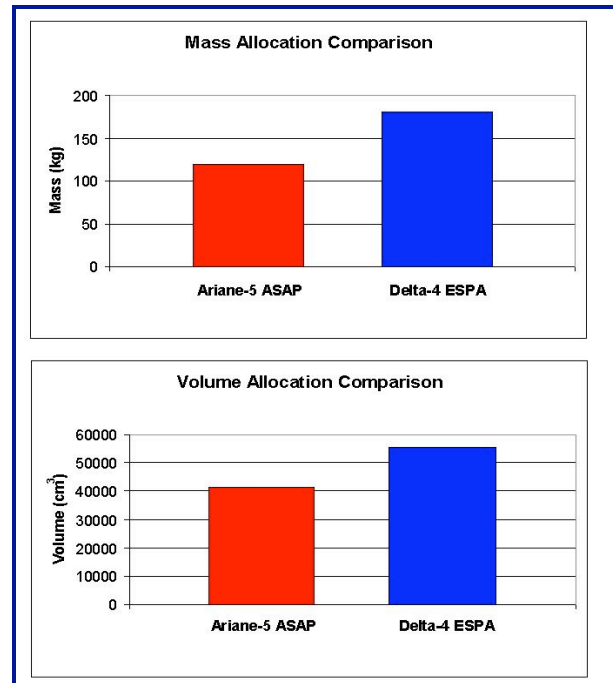
At first blush, there appear to be many similarities between the ESPA ring and the Ariane 5 ASAP (Ariane Structure for Auxiliary Payloads) ring for launching secondary payloads. On closer inspection, a number of significant differences become obvious.

The first significant difference is that the payload allocation for the ESPA ring is larger, both in mass and volume, than the ASAP ring (Figure 2). The second major difference is that the secondary payloads are mounted horizontally and separate from the ESPA ring in the radial direction (Figure 3). It is this mounting configuration that results in both the versatility of the ESPA ring and the greatest challenges for the ESPA payload designers.

### Launching Sideways

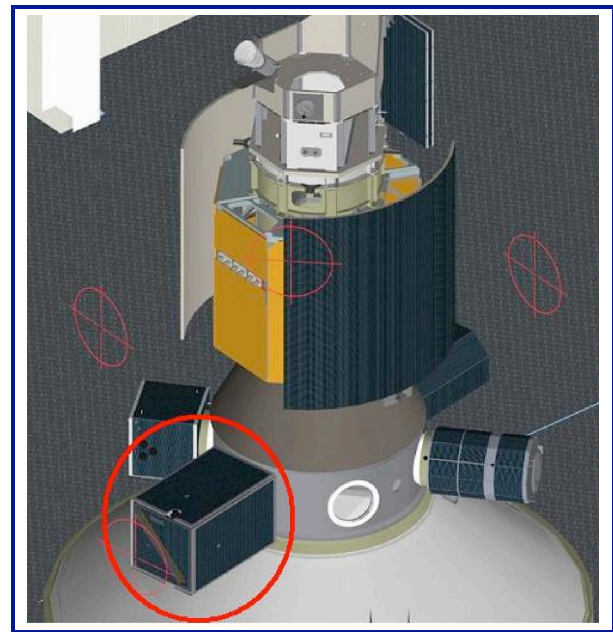
#### **Benefits**

The first major advantage of the ESPA design is that it is encapsulated within the same fairing as the primary payload. Once that fairing is jettisoned and the launch



**Figure 2. ESPA Mass and Volume Comparison.**

vehicle is on orbit, it can eject primary and secondary payloads in any predetermined sequence. In this way, the secondary payloads are not restricted to the same orbit as the primary as is the case with the Ariane ASAP ring. In fact, the original STP-1 mission had the launch vehicle stopping in a circular orbit and releasing all of the secondary payloads prior to proceeding to Geosynchronous Transfer Orbit (GTO) with the primary payload.



**Figure 3. STPSat-1 on the ESPA Ring.**

Another advantage to the radial mounting of secondary payloads on the ESPA ring is the accessibility of the secondary spacecraft after encapsulation via standard fairing access doors. The Delta-IV/ESPA combination allows the use of a standard Delta-IV 4-meter diameter fairing to encapsulate both the primary payload and the secondary payloads. This is different than the approach used on the ASAP ring, where the secondary payloads are inside a load-bearing structure, which is inside the primary fairing, making it impossible to access the secondary payloads once the launch vehicle integration has been completed. The accessibility of the ESPA ring through the standard fairing door feature allows for checking spacecraft state of health, charging batteries and removing inhibit plugs while on the launch pad within only a day or two of launch.

### Challenges

While there are some advantages to the ESPA ring design, there is one significant drawback – the design results in a cantilever-mounted spacecraft structure. Not only is this different from virtually every other launch vehicle in use today, where the thrust axis of the launch vehicle is typically parallel to the separation system axis, but more importantly, this configuration imposes more stringent requirements on certain aspects of the spacecraft structure. A typical mounting configuration puts the spacecraft in compression, while in the cantilevered configuration of the ESPA ring, the bending of the structure is the major concern. While this obstacle is certainly not insurmountable, it poses a very different set of problems than what are typically encountered in secondary spacecraft design and development.

Some of the requirements placed on the critical dimensions of ESPA-class payloads are shown in Table 1 below.

**Table 1. ESPA Payload Critical Dimensions**

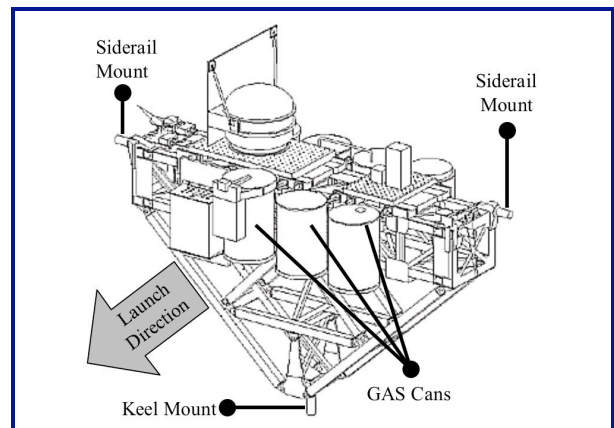
Critical Dimension	Requirement
Width	24 in (60 cm)
Height	24 in (60 cm)
Length (from flange mount)	38 in (96 cm)
Center of Gravity (from flange mount)	19 in (48 cm)
Separation System Bolt Diameter	15 in (38 cm)
Mass	375 lb (170 kg)
First Fundamental Frequency	35 Hz

While the payload can be as much as 24 inches wide, and the center of gravity (C.G.) location can be as much as 18 inches from the flange interface, the bolt circle diameter holding the entire assembly onto the launch vehicle is only 15 inches. This can significantly add to the lever arm of the payload, making the separation system attachment to both the launch vehicle and the spacecraft one of the more critical interfaces.

### Space Shuttle vs. ESPA

#### Similarities

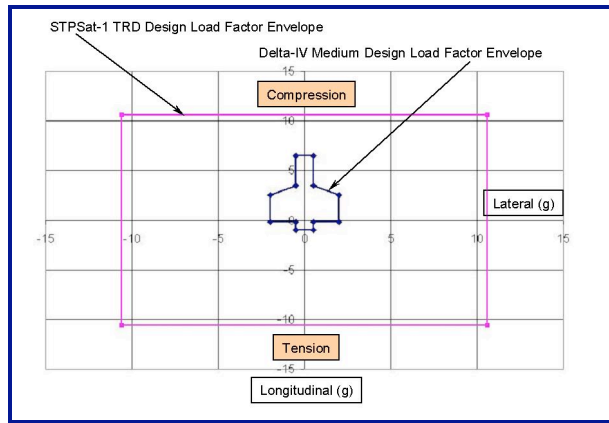
There is one other launch vehicle that routinely mounts payloads cantilevered to the thrust direction, the U.S. Space Shuttle. The Shuttle has been launching small payloads in the “Get Away Special” Canister Assembly (GAS Can) and as Shuttle “Hitchhiker” missions on the Mission Peculiar Experiment Support Structure (MPSS) for many years (Figure 5). While these accommodations are smaller than those for the ESPA standard bus, these missions have been very successful and clearly show that while unusual, it was not unreasonable for the ESPA developers to think that it would be possible to build a spacecraft structure that could launch in a cantilevered orientation.



**Figure 4. Space Shuttle MPSS**

#### Differences

There is one major difference between launching cantilevered on the Space Shuttle and the Delta-IV ESPA ring: the launch environment. Because there have been so many Space Shuttle flights and because the vehicle is so heavily instrumented, the launch environment – acoustic, vibration, shock and thermal levels – were well characterized and understood prior to the first attempts to launch these small secondary payloads. In addition, as a man-rated vehicle, the environment is required to be relatively gentle, significantly gentler than that of an expendable launch vehicle such as the Delta-IV.



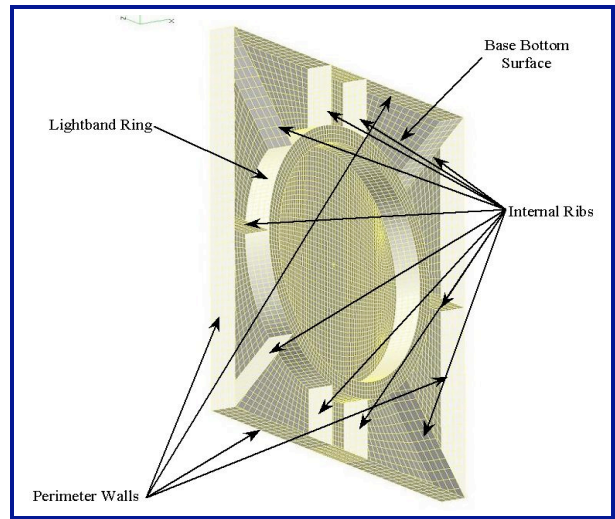
**Figure 5. STPSat-1 Quasi-Static Load Envelope.**

The Delta-IV is a new and significantly more capable expendable launch vehicle than the earlier Delta vehicles. However, at the time that the STPSat-1 contract was issued, the first Delta-IV flight was nearly 18 months away, well after the target date for the STPSat-1 Critical Design Review (CDR). To serve as a guideline until better information was available, the Mission Requirements Document prepared by the Space Test Program Office levied a 35Hz first fundamental frequency and a quasi-static load of 10.6 g's in two axes simultaneously. This gives a resultant vector sum of 18.75 g's, using a 1.25 design margin based on yield criteria (Figure 5). This left the design team with a blank sheet of paper, a static envelope and a nearly 20 g target to design to – significantly greater loading than for any other secondary payload accommodations and in bending rather than compression.

### The Solution

With the prospect of having to build a structure capable of withstanding 20 g's, AeroAstro rapidly concluded that many of the traditional spacecraft construction methods would have difficulty coping with the loads it could expect to see.

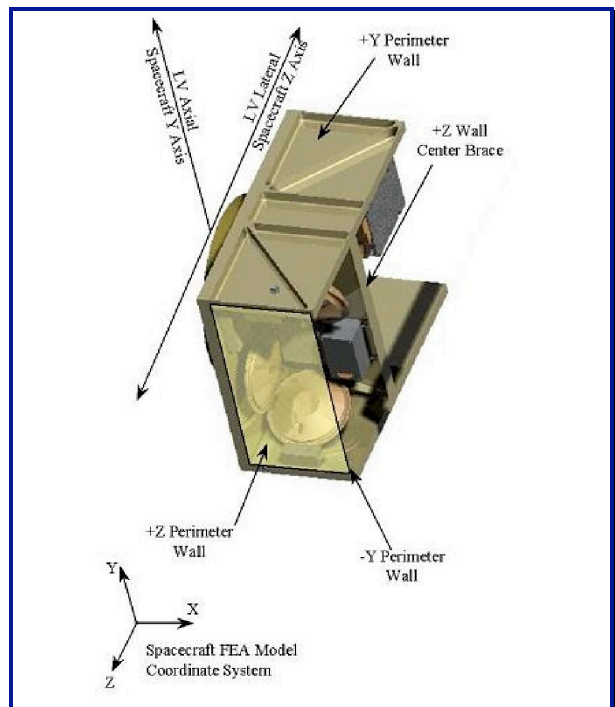
In many small spacecraft, the separation ring interface would be built on a honeycomb panel. Because of the large lateral loads, this would likely result in the skins delaminating from the honeycomb core. To counter this, AeroAstro designed a two-piece baseplate hogged out of a 6061 aluminum plate (Figure 6). A solid 1-inch wide ring was left in the center of each plate to be drilled and tapped for the separation ring. Internal ribs, each 5 millimeters wide, radiate out from the ring to the perimeter walls to provide stability to the 3-millimeter thick face sheets. The two halves are then vacuum-brazed together to produce a 23" x 23" x 1" plate that is nearly as stiff as an equivalent solid block of aluminum



**Figure 6. STPSat-1 Separation Interface Plate.**

but significantly lighter. This is not to suggest that the baseplate is lightweight. At over 6 kg, it is significantly heavier than a honeycomb plate that would be used if given a typically small lateral load.

Extending outwards nine inches from this baseplate are three walls machined out of a 1-inch thick aluminum plate (Figure 7). There is one wall on each the top and bottom (keeping in mind that the baseplate is mounted vertically) and the third center brace runs across the plate between the top and bottom, giving the impression of an I-beam extending out from the baseplate, further



**Figure 7. STPSat-1 Avionics Assembly.**



stiffening and strengthening the basic structure. These walls are bolted onto the flat surface of the baseplate on the opposite side as the separation ring.

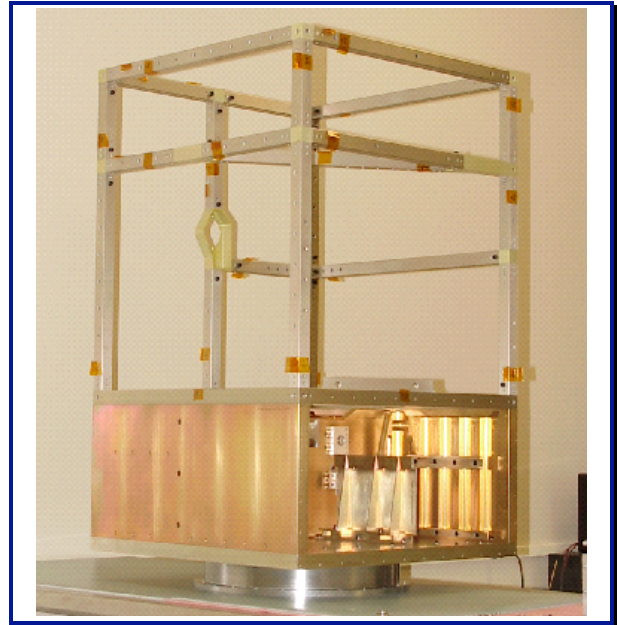
This baseplate also provides a mounting surface for much of the heavy, major spacecraft avionics components – such as momentum wheels, batteries, transponder, and electronics – in the two bays formed where the center wall bisects the baseplate. This avionics module provides a very stiff foundation for the mounting of the science instruments in the payload module.

The space within the North and South bays of the avionics module is extremely tight when the payload module is integrated to the avionics module. Experience tells us that many of the command and data handling components of the avionics system and the batteries will need to be accessed for troubleshooting during the vehicle integration. To simplify this troubleshooting, the major components – such as the IEM (Integrated Electronics Module), battery, battery charge electronics, and the transponder – are built up on pallets that slide into the avionics module and are clamped in place with wedgelock retainers. This is similar to the way that the cards are mounted within the electronics boxes – a sort of mechanical version of “plug-and-play.” Most of these avionics components are mounted directly to the brazed baseplate, keeping their moment arm as short as possible. The STPSat-1 Engineering Development Unit (EDU) avionics module is shown in the picture of Figure 8.

Mounted atop the avionics module is the payload module. Since a significant fraction of the total system mass is located within the avionics module, the payload module does not need to carry as significant a load and does not need to be as robust. For the structure, AeroAstro is using its SpaceFrame modular spacecraft architecture. This tube and fitting construction method is being developed under an Air Force Research Laboratory Small Business Innovation Research (SBIR)



**Figure 8. STPSat-1 EDU Avionics Module.**



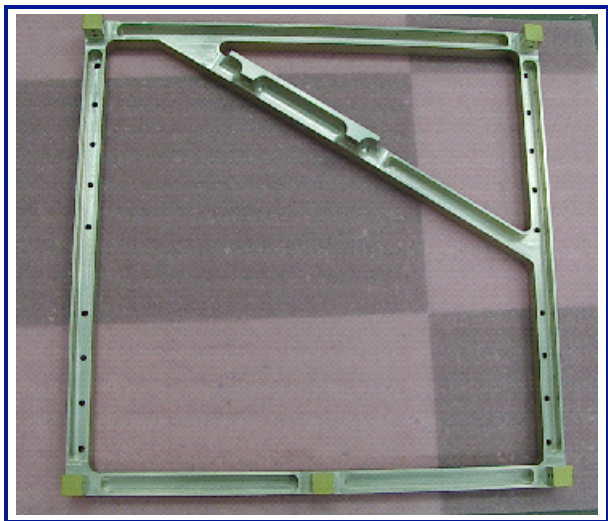
**Figure 9. STPSat-1 EDU SpaceFrame Structure.**

contract. The engineering model of the SpaceFrame technology is serving as the STPSat-1 EDU (Figure 9).

This approach had a number of advantages for this application. The first advantage is that it can be produced fairly inexpensively using commercially available extruded aluminum tubes. The second major advantage is its versatility. It must be remembered that the purpose of STPSat-1 is to provide a platform for a number of DoD Space Experiment Review Board (SERB) science payloads, each one with its own unique requirements and provided by several different organizations. To accommodate all of these different requirements, additional secondary bracketry is used to mount components, and these secondary brackets are attached to the primary structural tubes using commercial Rivnuts® as shown in Figure 10.



**Figure 10. Rivnut® Installed in Tube.**



**Figure 11. STPSat-1 Payload Module Base.**

The entire tubular structure was built up on a solid machined base (Figure 11). This provides a good foundation to build up the tubular structure as well as provide additional stiffness to the top of the avionics module by closing out the unsupported edges of the vertical walls.

After the tubes were machined and primed for bonding, the Rivnuts were installed. The tubes were then bonded to the joints while mounted to a rigid assembly fixture. This was done to ensure that the assembled module was kept as square as possible. AeroAstro had originally intended to assemble the payload module using only bolted joints. However, our analysis indicated that some of the fastened joints could fail at 20 g's, and for this reason, a combination of both bolted and bonded joints is being used (Figure 12).



**Figure 12. Typical Payload Module Bonded Tube Joint.**

Because of the care and attention to detail during the design phase, the final integration of the STPSat-1 EDU with mass models went off without any hitches or rework. The completely assembled EDU structure can be seen in Figure 13.

### **Lessons Learned From This Experience**

Designing a spacecraft, or any structure, with incomplete information is risky and difficult. Adding to that a new launch configuration only serves to complicate the job. However, the rationale for pushing the design process to these extremes is not without some basis.

While the Delta-IV is a new launch vehicle, it has the historical precedent of earlier Delta launch vehicles to rely on and extensive ground testing of many of the components. The ESPA ring is a remarkably simple and elegant solution to the problem of launching secondary payloads, but there is no real historical precedent on which to rely.

For this reason, the flight of STP-1 must be viewed as a test flight of the Delta-IV/ESPA ring combination and will set the precedent for any following flights. The consequences of failure would significantly reduce the



**Figure 13. Finished STPSat-1 EDU Structure.**

likelihood of future ESPA flights as well as place a valuable primary payload at risk, but there will be no prior test flight from which to gather data. There is only one chance to get it right.

For this reason, AeroAstro took a back-to-basics approach to designing the spacecraft structure. There are no exotic composites used as structural components and no revolutionary bonding or machining techniques used – just the judicious use of well-documented and well-understood engineering methods.

The prospect of designing a spacecraft structure for a 20 g quasi-static load can be daunting on its own, as can designing for a horizontal launch orientation. The thought of combining the two on a new and untested platform can be enough to make even a seasoned engineer lose sleep at night.

The first piece of advice for anyone designing for ESPA is to not be intimidated by the loads or the orientation. While cantilevered may be unusual for a spacecraft, it is quite typical for other types of high-performance vehicles, such as aircraft. In fact, the primary structure of STPSat-1 in some ways mimics a wing spar with the I-beam structure extending out from the base.

The idea of designing a spacecraft structure to 20 g's is a little harder to accept. Everyone understands that it is virtually impossible for the launch vehicle to impart these kinds of loads to the ESPA payload, so why design and test to them? Quite simply, that is the hurdle that one must get over to provide a level of comfort to the primary payload and the launch vehicle that the secondary payload does not represent a risk to their mission. It is possible that the load levels could be reduced after some actual flight data is available, but that is still several years away. And even then, it is likely that secondary payloads will be required to design and test to higher levels, just to provide that

level of comfort to the primary payload and the launch vehicle.

One nice aspect of the ESPA-class payload is that the 180 kg mass allocation is somewhat generous for the volume. This has allowed us to add sufficient primary structure mass without resorting to exotic manufacturing or materials. The primary structure is built entirely of aircraft-grade 6061 Aluminum. Bolted interfaces are made with standard 160ksi stainless bolts and bonded joints use Dexter-Hysol EA-9303 components that can be found on many other spacecraft designs.

As stated earlier, the ESPA ring represents the most significant addition to the secondary launch capacity and is the only major US launch system to offer that option. Since it is so versatile, it can be effectively used both for DoD payloads and commercial scientific missions. In many ways, STPSat-1 is the pathfinder for the payloads designed to meet the ESPA standard. It fits within the standard ESPA mass and volume constraints, and when completed, it will provide a template for the documentation, design and manufacturing processes necessary to streamline the process for those payloads that follow on future ESPA flights.

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